Estimating Reference Crop Evapotranspiration with ETgages

Fan Chen[1] and Peter J. Robinson[2]

Abstract: Three years of daily reference evapotranspiration measured by atmometers (ET_g) were compared to the values computed from the ASCE standardized Penman–Monteith equation (ET_r) using co-located meteorological measurements at 19 locations across North Carolina. The atmometers underestimated daily ET_r by an average of 21% across the study area. Linear regression models between ET_g and ET_r had intercepts significantly different from zero and slopes different from one, but would generally yield a gauge error within 1 mm day^{-1}. The ET_g-ET_r relationship was found to be highly sensitive to precipitation and wind speed, but rather insensitive to humidity, radiation, and temperature. Although wind speed is generally low in the study area, the insensitivity of ETgages to wind caused severe underestimation in those periods when wind speed was high. Mean absolute error increased from 17% when wind speed was below 1 m s^{-1} to 64% when wind speed was greater than 5 m s^{-1}. Precipitation can temporarily disrupt ETgage evaporation and cause underestimation of ET_r. The linear relationship between ET_g and ET_r in rainy days was significantly different than that of the clear days. Analysis of the local relationships suggested that they are sensitive to their major surrounding physiographic environment and to the strictly local surface conditions, but not to the intermediate mesoscale surface environment. As a result, different linear regression equations were developed to adjust ET_g to ET_r in three land regions and in dry or wet conditions.

DOI: 10.1061/(ASCE)IR.1943-4774.0000005

CE Database subject headings: Evapotranspiration; Crops; Estimation; North Carolina.

Introduction

Reliable estimation of crop water use, or evapotranspiration (ET), is crucial for irrigation scheduling and water management. In general, evapotranspiration of the crop of interest is obtained by multiplying the rate of reference evapotranspiration by a predetermined crop coefficient. Direct computation of reference evapotranspiration using semiphysically based equations is available using the various forms of Penman or Penman–Monteith equations (Jensen et al. 1990; Allen et al. 1998). However, these equations usually require measurement of meteorological observations such as temperature, humidity, solar radiation, and wind speed, which cannot be satisfied in many areas. For many decades evaporation pans have been widely used to measure evapotranspiration. When properly maintained, pan evaporation is highly correlated to reference crop evapotranspiration and can be used to estimate the latter by multiplying a pan coefficient (Doorenbos and Pruit 1977). Pan coefficients are usually determined from fetch distance, wind speed, and relative humidity either by using a lookup table (Doorenbos and Pruit 1977) or an equation (Cuenca 1989; Snyder 1992; Pereira et al. 1995; Raghuwanshi and Wallender 1998; Frevert et al. 1983; Allen et al. 1998). However, evaporation pans often have a bias due to their heat-storage problems, and are subject to various external disturbances (Allen et al. 1998).

In recent years, a relatively simple type of modified Bellani plate atmometer (Altenhofen 1985) under the brand name ETgage, has gained increasing popularity. It consists of a wet, porous ceramic cup mounted on top of a cylindrical reservoir filled with distilled water, and a suction tube that extends to the bottom of the reservoir. The flat or convex-shaped ceramic cup is covered with a green canvas that simulates the diffusion resistance for water vapor through the natural reference grass (#30 canvas) or alfalfa (#54 canvas) surface. Underneath the canvas cover, a polytetrafluoroethylene (PTFE) membrane could be introduced to keep rain water from seeping into the ceramic cup. The evaporating surface is 1 m above the ground. The designed accuracy of the ETgage is ±1% of evaporated water, with a resolution of 0.01 in. (0.254 mm). The capacity of the reservoir is 12 in. (304.8 mm) of water depth. Studies have indicated small variations between individual ETgages (Irmak et al. 2005; Broner and Law 1991). For a detailed description of the ETgages, see Altenhofen (1985, 1992), Alam and Trooien (2001), and Irmak et al. (2005).

The use of ETgages has proven to be a feasible and practical alternative to calculations using the Penman or Penman–Monteith equations, with proper local regression equations being developed (Broner and Law 1991; Alam and Trooien 2001; Magliulo et al. 2003; Irmak et al. 2005; Alam and Elliot 2003; Blanco and Folegatti 2004). However, there are concerns about their performance in wet weather (Irmak et al. 2005). In North Carolina a network of ETgages have been established at existing sites where data required by the Penman–Monteith equation are measured. Therefore, comparisons between the two methods at a variety of locations in a humid climate were possible. Our goal is to test whether the ETgages could be used as a simple substitute for the Penman–Monteith method and investigate the physics behind their differences. Therefore the specific objectives were to: (1) compare daily ETgage observations (ET_g) with Penman–Monteith predictions of reference evapotranspiration (ET_r) at

[1]Visiting Scientist, USDA-ARS Hydrology and Remote Sensing Laboratory, 104 Bldg. 007, BARC-West, Beltsville, MD 20705 (corresponding author). E-mail: Fan.Chen@ars.usda.gov

[2]Professor, Dept. of Geography, Univ. of North Carolina, 222 Saunders Hall, CB 3220, Chapel Hill, NC 27514.

Note. This manuscript was submitted on April 16, 2008; approved on October 16, 2008; published online on January 22, 2009. Discussion period open until November 1, 2009; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, Vol. 135, No. 3, June 1, 2009. ©ASCE, ISSN 0733-9437/2009/3-335–342/$25.00.

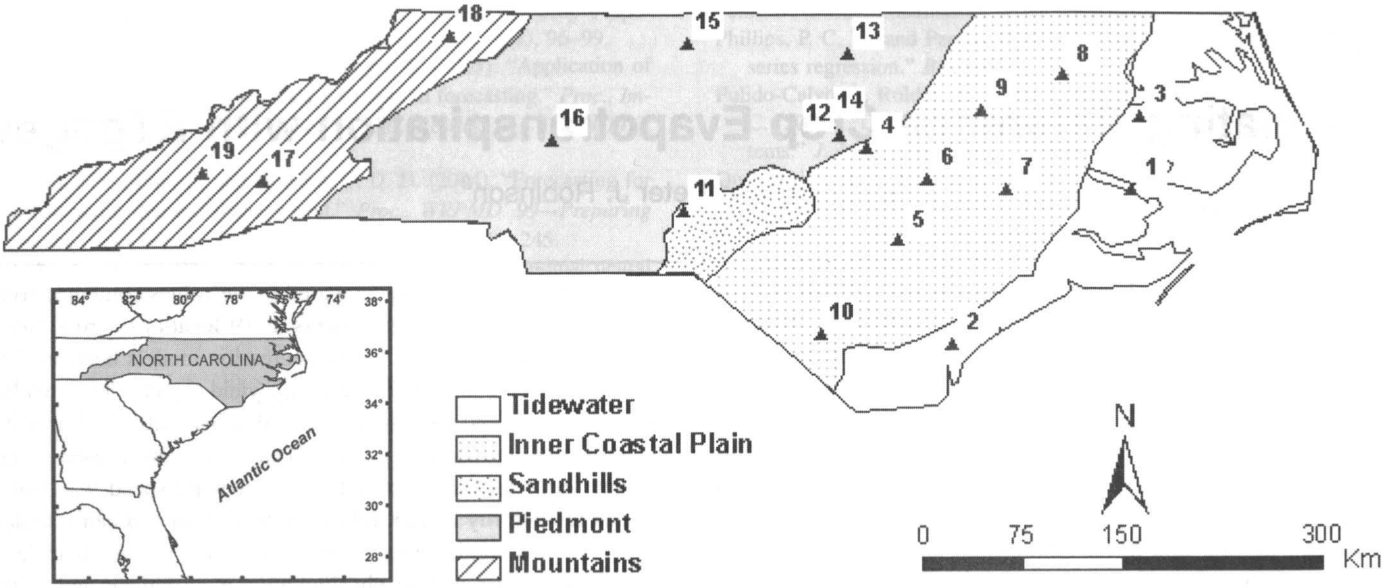

Fig. 1. Division of physiographic regions and location of ET gauge stations

various sites with differing topographical and pedological conditions; (2) investigate the differences of ET_g and ET_r in terms of their response to the atmospheric drivers as well as rainfall; and (3) develop transfer functions, if applicable, that adjust ET_g to Penman–Monteith estimates.

Study Area and Data

The study area covers the land surface of North Carolina with the exception of the Outer Banks, the narrow chain of islands in the Atlantic Ocean. North Carolina lies between 33.5 and 37°N, and 75 and 84.5°W. The east to west breadth is 810 km and the extreme distance from north to south is 301 km. This part of the southeastern United States generally has a humid subtropical climate characterized by short mild winters and humid summers. The region is primarily influenced by the position of the Jet Stream and the maritime air masses which originate over the Atlantic Ocean, including the Gulf of Mexico. In the cool seasons, the Jet Stream directs cyclones from the Gulf of Mexico that bring widespread precipitation to the area. In the warm seasons the Jet Stream commonly retreats far to the north of the region, and tropical air masses from the Atlantic Ocean bring hot and humid weather characterized by thunderstorms, clear sky, and strong insolation. Other than the parts of the western mountains that are influenced by orographic or rain shadow effects, average annual rainfall ranges mostly between 1,000 and 1,400 mm. There are no distinct wet and dry seasons in North Carolina, although summer is normally the wettest season and fall the driest.

Traditionally, the state is divided into three physiographic provinces: the Coastal Plain, the Piedmont Plateau, and the Blue Ridge/Appalachian Mountains. However, to investigate the topographic and biotic influence on the relationships between ET_g and ET_r, a five-region division was used here (Fig. 1). The Coastal Plain was divided into two parts: the Tidewater and the Inner Coastal Plain. Tidewater tends to be dominated by swampy forests, although agriculture on drained lands is also important, while the Inner Coastal Plain is well drained and highly agricultural with many softwood plantations. The distinctly sandy area of the Sandhills divides the Piedmont's clay soil from the sandy loam of the Coastal Plain, and the fast-draining soil is associated with warm springs, mild winters, and increased summertime thunderstorm activity. The relatively dry Sandhills soil strongly influences the vegetation, leading primarily to coniferous forest. The Piedmont plateau region has a mix of deciduous and coniferous forest, agriculture, and urban development. The vegetation of the mountain region is primarily northeastern hardwoods forest, with relatively small areas of cultivated land.

ETgages have been added to the North Carolina's Environment and Climate Observing Network (ECONet) stations since 2003. By 2006 there were 20 ETgage sites that covered all five physiographic regions. These automatic ETgages are generally within 3 m from the main weather towers with synchronized dataloggers. The #54 green canvas covers for alfalfa reference ET were used in all sites and the evaporating surfaces were 1 m above ground. Most sites are located within an agricultural research facility and are either surrounded by or on the side of an agricultural field.

Daily ET_g values determined as the sum of 24 hourly readings were used throughout the study. Gauges were shut down to avoid freezing damage in the cold seasons; therefore the actual available period differed somewhat by site and year. Thus, observations were generally available from late April–early May to mid October, but the period was several weeks shorter in the mountains. Since there was no a priori knowledge of expected means and standard deviations of the dataset, two preliminary quality assurance/quality control (QA/QC) procedures were performed: (1) consecutive days with zero readings, followed by an exceptionally high value, were assumed to be accumulative readings and were all excluded; and (2) other days with zero readings during the nonfreezing period were assumed to be spurious and were removed. Such days appeared to be randomly scattered through the data, and together averaged about 6 days/station/year. Furthermore, the possible contaminating effect of sensible heat advection and erroneous high readings were minimized by removing daily ET_g values that were greater than 1.5 times the equivalent water depth determined by the observed incident radiation. A total of 207 days were removed for this reason. By visual comparison of ET_g and ET_r values, another 23 days were

Table 1. Locations of ET Gauge Stations

Site ID	Name	Date of first observation	Region	Latitude	Longitude	Elevation (m)
1	Aurora	June 24, 2003	Tidewater	35.36	−76.72	4
2	Castle Hayne	June 18, 2003	Tidewater	34.32	−77.92	43
3	Plymouth	April 13, 2005	Tidewater	35.85	−76.65	20
4	Clayton	April 7, 2005	Inner coastal plain	35.67	−78.49	350
5	Clinton	April 30, 2004	Inner coastal plain	35.02	−78.28	166
6	Goldsboro	April 13, 2005	Inner coastal plain	35.38	−78.04	79
7	Kinston	May 3, 2004	Inner coastal plain	35.30	−77.57	95
8	Lewiston	June 19, 2003	Inner coastal plain	36.13	−77.18	61
9	Rocky Mount	April 14, 2005	Inner coastal plain	35.89	−77.68	88
10	Whiteville	April 29, 2004	Inner coastal plain	34.41	−78.79	89
11	Jackson Springs	June 5, 2003	Sandhills	35.19	−79.68	625
12	Lake Wheeler	September 14, 2003	Piedmont	35.73	−78.68	382
13	Oxford	May 3, 2004	Piedmont	36.30	−78.62	500
14	Reedy Creek	April 16, 2005	Piedmont	35.81	−78.74	420
15	Reidsville	May 3, 2004	Piedmont	36.38	−79.70	858
16	Salisbury	June 17, 2003	Piedmont	35.70	−80.62	703
17	Fletcher	May 5, 2004	Mountains	35.43	−82.56	2,067
18	Laurel Springs	May 1, 2004	Mountains	36.40	−81.30	3,009
19	Waynesville	June 28, 2003	Mountains	35.49	−82.97	2,755

identified as suspect outliers and were also removed. After the quality control process, 5,865 daily data points collected between June 2003 and October 2005 from 19 ECONet stations (Table 1) were retained for further analysis.

Methodology

The ET_g data were compared against ET_r calculated from the ASCE standardized Penman–Monteith equation (Allen et al. 2005), i.e.

$$\mathrm{ET}_r = \frac{0.408\Delta(R_n - G) + \gamma\dfrac{C_n}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \tag{1}$$

where ET_r=standardized reference crop evapotranspiration for alfalfa surfaces (mm day^{-1}), R_n=calculated net radiation at the crop surface (MJ m^{-2} day^{-1}), G=soil heat flux density at the soil surface; and G=0 MJ m^{-2} day^{-1} for daily time steps; T=mean daily air temperature at 1.5–2.5 m height (°C); u_2=mean daily wind speed at 2 m height (m s^{-1}); e_s=saturation vapor pressure at 1.5–2.5 m height (kPa), calculated as the average of saturation vapor pressure at maximum and minimum air temperatures; e_a=mean actual vapor pressure at 1.5–2.5 m height (kPa); Δ=slope of the saturation vapor pressure-temperature curve (kPa °C^{-1}); γ=psychrometric constant (kPa °C^{-1}); C_n and C_d=surface-dependent constants; and C_n =1,600 K mm s^3 Mg^{-1} day^{-1} and C_d=0.38 s m^{-1} for alfalfa with an approximate height of 0.50 m.

Due to variations in the surrounding land cover and maintenance practice, the observed meteorological conditions at the ETgage sites may not reflect those of a well-watered reference surface. Therefore, procedures given by Allen (1996) and Temesgen et al. (1999) were applied to adjust the observed temperature and humidity data to well-watered conditions before the calculation of ET_r (see Appendix).

Much of the analysis uses straightforward linear regression techniques. Besides the commonly used coefficient of determination, R^2, modified index of agreement (d_1) was also used to minimize the potential bias due to the presence of outliers (Willmott 1982). Modified index of agreement has been used as a method-selection criterion in water resources investigations and is defined as

$$d_1 = 1.0 - \frac{\Sigma_{i=1}^{n}|O_i - P_i|}{\Sigma_{i=1}^{n}(|P_i - \overline{O_i}| + |O_i - \bar{O}|)} \tag{2}$$

where O and P=observed and predicted data, respectively; the overbar indicates a mean value; and n=number of observations (Legates and McCabe 1999). The value of d_1 varies from 0 to 1, with 1 indicating a perfect fit between the simulated and the observed data. Although it may be interpreted in a similar fashion as the R^2, d_1 is considered superior because it is less sensitive to outliers and proportional differences than R^2. Percent mean absolute error (MAE%), defined as

$$\mathrm{MAE}\,\% = \frac{\overline{|P - O|}}{\bar{O}} \cdot 100 \tag{3}$$

was also used as a measure of ET_g's relative deviation from ET_r.

Results and Discussion

Initially ET_g data from all sites were combined and plotted against ET_r (Fig. 2). Daily ET_g values ranged from 0.25 to 9.65 mm and were well correlated to ET_r (d_1=0.65, R^2=0.75). The slope and intercept of the linear regression equation (ET_r =0.81 ET_g+1.53) and standard error (0.75 mm day^{-1}) were close to the values reported by Alam and Trooien (2001) in western Kansas. However, ET_g was lower than ET_r on 84.6% of the days and the average $\mathrm{ET}_g/\mathrm{ET}_r$ ratio was only 0.79. Furthermore, ET_r

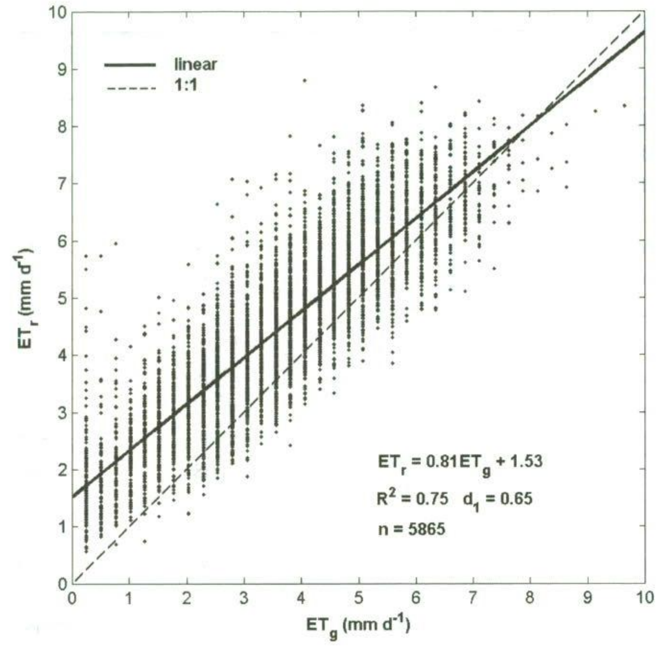

Fig. 2. Comparison of daily ET_g and ET_r, all locations

was underestimated on 98.6% of the days, and by an average of 45.5% when ET_g was lower than 2 mm day^{-1}. This result suggested the need to adjust ET_g with a linear regression equation. The following sections examine the spatial variations of, and the influence of atmospheric drivers and rainfall on, the ET_g-ET_r relationship.

Spatial Variations

Individual stations had a scatter of points similar to the aggregated results in Fig. 2. Statistics evaluating the correlation between ET_g and ET_r at individual locations were mapped in Fig. 3. In general the ET_r-ET_g correlation was good and showed no clear spatial pattern across the study area. The best agreement (d_1=0.74, RMSE=0.76 mm day^{-1}) was found in Salisbury of west-central Piedmont, while the poorest (d_1=0.48, RMSE =1.9 mm day^{-1}) was found in Plymouth in the northeastern Tidewater region. Very low values of d_1 were also found at Goldsboro (central Coastal Plain), Jackson Springs (central Piedmont), and Laurel Springs (northern Mountains). Both the greatest slope (0.96 at Kinston) and the smallest slope (0.59 at Reedy Creek) were considerably different from their nearby stations. This may suggest the effect of local-scale microclimate conditions or the instrumental variations, and requires further investigation. Nevertheless, the standard error estimate (SEE) indicates that after calibration with locally developed linear regression equations, ETgage estimation errors were commonly less than 0.8 mm day^{-1}.

The general agreement (d_1) between ET_g and ET_r, calculated using all the data points falling in each region, varied only slightly for the five subregions (Table 2). The SEE estimates suggested that adjustment of ET_g to ET_r using the appropriate linear regression could reduce RMSE by more than 30%, resulting in errors much smaller than 1 mm day^{-1}. The similarity in the regression coefficients between the Tidewater and Inner Coastal Plains and between the Piedmont and Mountains regions suggested the feasibility of these regions being combined in developing ET_g-to-ET_r transfer functions. The Piedmont-Mountain combination indicates that the results are not sensitive to broad scale topographic effects. Although the distinction between the Tidewater and the Inner Coastal Plain had been made because the former is rather swampy, the latter is not, and all stations in both regions are located on well-drained land. Hence the similarity between the two suggests that local, perhaps microscale, surface factors are more significant than the wider mesoscale ones. The distinctly higher intercept for the only Sandhills station indicated the need to treat this region separately from others; and additional observation sites are desired to develop a better representative relation.

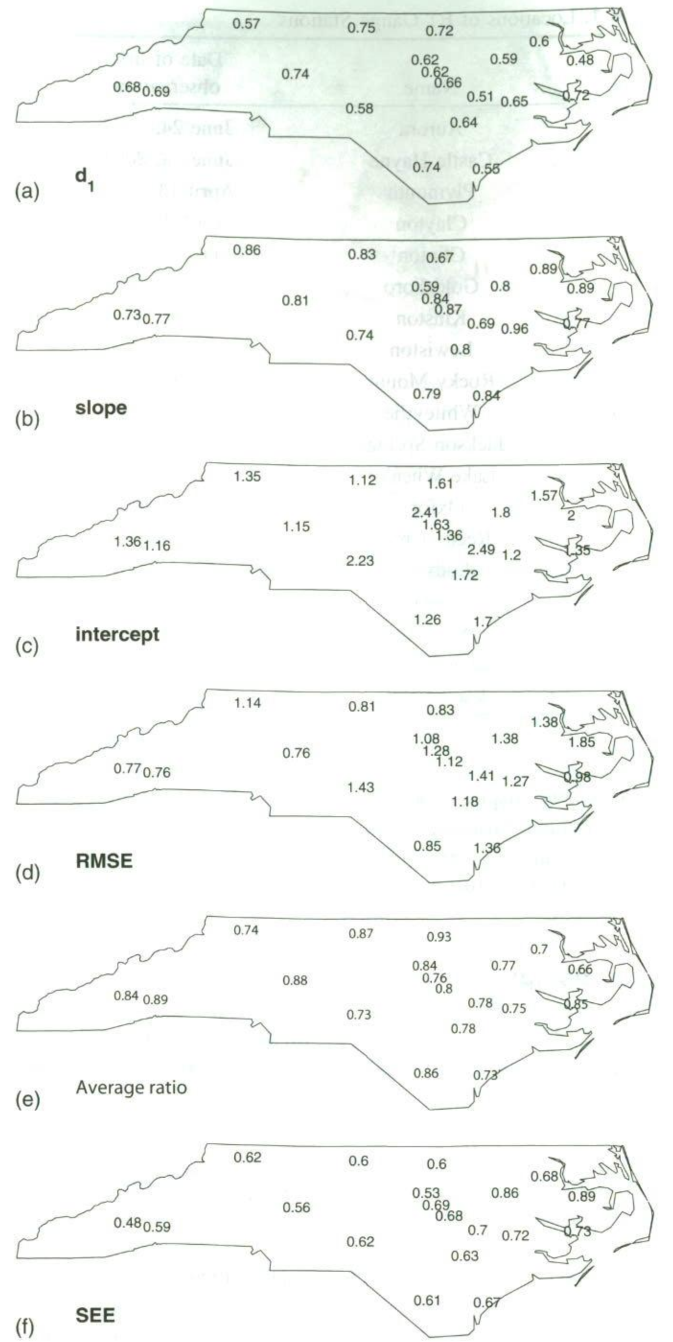

Fig. 3. ET_r-ET_g relationship at individual stations

Table 2. Statistics of ET_r–ET_g Relation by Region

Region	d_1	R^2	RMSE	MAE (%)	Slope	Intersect	Avg. ratio	SEE[a]
Tidewater	0.60	0.74	1.34	27.5	0.84	1.62	0.75	0.80
Inner coastal plain	0.65	0.78	1.18	23.2	0.84	1.47	0.79	0.74
Piedmont	0.68	0.76	1.02	20.6	0.76	1.56	0.84	0.71
Sandhills	0.58	0.82	1.43	27.4	0.74	2.23	0.73	0.62
Mountains	0.65	0.73	0.89	21.7	0.76	1.34	0.83	0.6
All locations	**0.65**	**0.75**	**1.17**	**23.7**	**0.81**	**1.53**	**0.79**	**0.75**

[a]SEE=standard error of estimate.

ETgage Performance under Different Climate Conditions

Paired ET_g-ET_r data from the entire study area were compared in different conditions of temperature, humidity, wind speed, and radiation (Table 3). Though not a direct driver of evapotranspiration, temperature was included to investigate the presence or heat storage-related problem in the ETgages. The range of each variable except wind speed was divided into quartiles (each quartile thus having an equal number of events). Since wind speeds are commonly rather low in North Carolina, especially during the high evapotranspiration period in summer, use of classes adapted from Allen et al. (1998), rather than quartiles, ensured four distinct ranges meaningful for analysis.

The results (Fig. 4) suggested that the ET_g-ET_r relation was most sensitive to wind speed. The failure of R^2 in capturing this important fact demonstrated its ineffectiveness in evaluating the instrument/model performance compared to d_1. As the wind speed increased, agreement between ET_g and ET_r deteriorated dramatically, with a steep, nearly linear decline in both d_1 and average ratio. MAE% increased from 17 for the lightest-wind class to 64

Table 3. Distribution of Daily Weather Data in Four Classes

Class	Temperature (°C)	VPD (kPa)	Wind speed (m/s)	Solar radiation (MJ m^{-2} day^{-1})
1	<18.9	<0.72	<1.0	<14.2
2	18.9–22.8	0.72–0.97	1.0–3.0	14.2–18.6
3	22.8–25.7	0.97–1.24	3.0–5.0	18.6–22.8
4	≥25.7	≥1.24	≥5.0	≥22.8

Note: Only days with valid ET_g data were included.

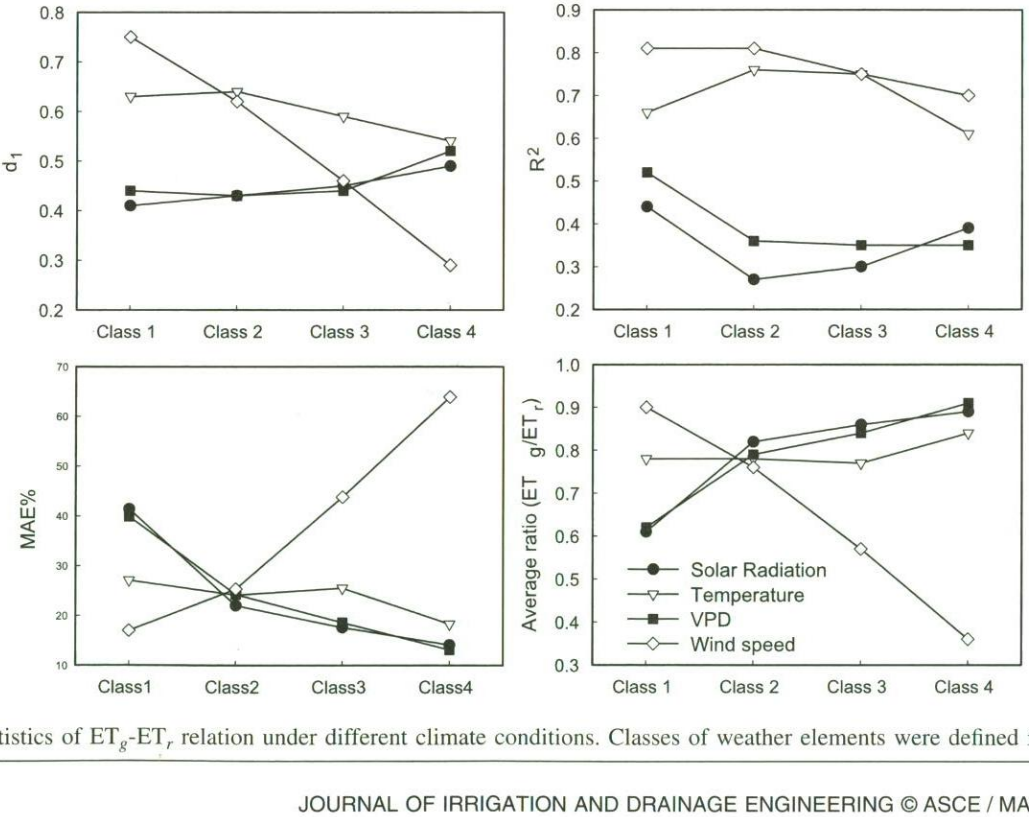

Fig. 4. Statistics of ET_g-ET_r relation under different climate conditions. Classes of weather elements were defined in Table 3.

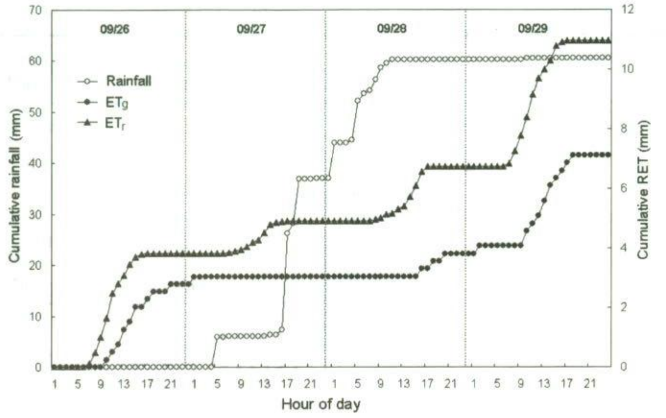

Fig. 5. Cumulative hourly ET_g, ET_r, and precipitation during September 25–29, 2004 at Jackson Springs

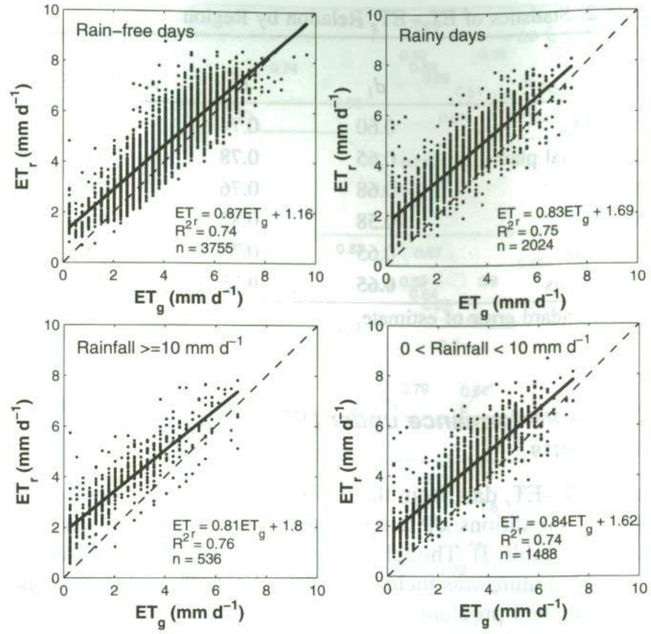

Fig. 6. Relationship between ET_g and ET_r in dry and different rainy conditions

for the strongest-wind class. Regardless of other variables, the best agreement between ET_g and ET_r was achieved when wind speed was below 1 m/s. Further examination revealed that ET_r had a positive correlation with wind speed, significant at the 0.05 level, in ten of the 19 stations, with the highest correlation coefficient (R) being only 0.26, and no significant correlation presented in the rest of the stations. Conversely, ET_g was found to be negatively correlated to wind speed at the 0.05 level in 11 stations, and had no significant correlation in the others. This suggested that in this region's generally low-wind climate, wind speed had a rather insignificant control over reference evapotranspiration. ETgages, due to their inadequate simulation of the aerodynamic properties of the reference surface, were even less sensitive to wind speed. Therefore, the insensitivity of ETgages to wind speed is believed to be the major cause of the large discrepancy between ET_g and ET_r at relatively high winds. The reason why R^2 didn't deteriorate quickly at higher wind speeds, like other indices did, was likely due to its using sum of squared errors, which blurred the fact that ET_g predominantly underestimated ET_r at higher wind speeds.

On the other hand, MAE% indicated the ETgage estimates were closest to ET_r in the highest quartiles of solar radiation, temperature, and vapor pressure deficit, i.e., in sunny, warm, and dry weather. The average ET_g/ET_r ratio was relatively stable across all temperature ranges, and remained well below 1.0 ($\sim$0.84) even in the highest quartile. This suggested that the common problem of mass-balance type atmometers of increased evaporation due to heat storage was insignificant in the ETgages in this region. Similar results were obtained when data are aggregated by the physiological subregions.

Effect of Rainfall

Extremely low ET_g values were observed to be related to rainfall events. A typical situation is illustrated by comparing hourly cumulative ET_g and ET_r between September 26 and September 29, 2004 at Jackson Springs (Fig. 5). After the 6 mm rain occurred in the early morning of September 27, no evaporation was recorded during the day while calculated ET_r continued to accumulate until 1500 hrs. On September 28, ETgage did not start evaporating until 1600 hrs, i.e., 4 h after the rain stopped. The observed lag of the ET_g readings could be attributed to the accumulation of rainwater on the evaporating surface.

A possible effect of rainfall accumulation on reduced ET_g was examined by comparing ET_g and ET_r in different rainy conditions. Fig. 6 suggested the proportion of days on which ET_r was underestimated greatly increased on rainy days. The smaller slope and much higher intercept for the rainy days than those of the dry days indicate the need for separate transfer functions for both conditions. To refine the analysis, days of light rain (total $<$10 mm) were separated from those with greater amounts. It appears that the heavier the rainfall, the smaller the slope and the larger the intercept tends to be. It is, however, unclear whether this is a result of more water accumulation or longer rainfall duration onto a wet dome. A more detailed analysis, using hourly information as demonstrated in Fig. 5, is necessary before the transfer functions can be further refined.

Summary and Conclusion

The ETgage atmometers were evaluated against the standardized Penman–Monteith equation for their ability to simulate alfalfa reference ET at 19 locations across North Carolina during the warm seasons of a 3-year period. Throughout the period gauge values of zero were assumed to be erroneous and not considered further. However, the occasional occurrence of zero readings, and of exceptional high values, suggests that further investigation of ETgage performance, and possible malfunctions, is needed.

The ETgage estimates (ET_g) were compared with the ASCE standardized Penman–Monteith equation for alfalfa (ET_r). The results suggested this type of atmometer could be used as a simple substitute for the Penman–Monteith method after certain quality control and conversion procedures. On average ET_g underpredicted ET_r by about 20%, and by 45% when ET_g was lower than 2 mm day^{-1}. This is much greater than that reported within 5% underprediction with canvas #54 in western Kansas (Alam and Elliott 2003), indicating the need to apply specific adjustments in different climates.

Table 4. Recommended Parameters to Adjust Daily ET_g to ET_r by $ET_r = a{*}ET_g + b$

Daily precipitation	Tidewater and inner coastal plain a	b	R^2	Piedmont and mountains a	b	R^2	Sandhills a	b	R^2
N/A[a]	0.84	1.55	0.76	0.77	1.42	0.76	0.74	2.23	0.82
=0	0.90	1.17	0.75	0.83	1.07	0.75	0.77	2.02	0.82
>0	0.85	1.71	0.75	0.79	1.57	0.77	0.79	2.26	0.82

[a]N/A = not available.

The ET_g-ET_r relations in North Carolina were found to be highly sensitive to precipitation and wind speed, but rather insensitive to humidity, radiation, and temperature. The average ratio between ET_g and ET_r is closest to one in dry, calm, and strong radiation conditions. At high wind speeds (above 5 m/s) an average of 60% underestimation was observed. In the study area wind speed is generally so low that it uncorrelated with both ET_g and ET_r in about half of the locations. However where a correlation was significant, it was positive for ET_r and negative for ET_g. This inconsistency appears to be largely responsible for the overall underestimation by the gauges. However, the characteristically light winds of the state make the development of transfer functions incorporating wind speed difficult. In practice the predominance of light winds allows for the general transfer of functions without modification, although care must be used when high winds occur. The reason for the negative correlation between ET_g and wind speed is unclear and warrants further investigation, which could significantly improve the ETgage performance in similar low-wind climates.

Precipitation frequently had a major impact on the gauge readings. Precipitation can cause low ET_g readings due to rainwater accumulation, so that ET_g values obtained on rainy days and subsequent days should be used with caution. Further investigation on the role of rainfall duration as well as the amount from hourly records is needed to better understand the ETgage performance in wet conditions. It may be possible; on the other hand, to suggest that the rainwater retention on the evaporating surface can be regarded as mimicking the natural rainfall interception, which brings up interesting questions about whether or to what extent this simulates the natural evapotranspiration process in rainy or irrigated conditions.

Simple linear regression between ET_g and ET_r yielded an intercept significantly different from zero and a slope different from unity. Hence it was possible to adjust ET_g to ET_r by fitted linear functions. Analysis of the individual stations results suggested that they are sensitive to their major physiographic environment and to the strictly local conditions, but not to the intermediate mesoscale surface environment. Therefore, although individual local models produce smaller standard errors than those developed from aggregated regional data, the improvement was trivial ($\sim$0.1–0.2 mm day^{-1}) compared to its complexity. Recommended transfer functions to adjust daily ET_g to ASCE-standardized ET_r were developed for three regrouped regions (Tidewater+Inner Coastal Plain; Piedmont+Mountains; Sandhills) and dry/wet conditions (Table 4). It should be noted that these functions should only be applied when temperatures are above freezing and when ETgage readings are nonzero and within a reasonable range. Due to its sandy surface and warm, dry climate, the Sandhills' distinct parameters were not unexpected, except that only one station was used. In the future more observations in additional locations are desired to establish more representative functions for this region.

Acknowledgments

The writers acknowledge and thank the two anonymous reviewers for their valuable suggestions on the manuscript.

Appendix. Procedure for Temperature and Humidity Adjustment for Reference Conditions

The following procedures adapted from Allen (1996) and Temesgen et al. (1999) were used to adjust temperature and dew point data measured at nonreference stations to well-watered conditions for reference evapotranspiration calculations. First, a mean dew point departure (MDD) index was calculated as an indicator of the extent of aridity of a weather station

$$\mathrm{MDD} = T_{\min} - T_d$$

where $T_{\min}$ and T_d=daily minimum temperature and mean dew point (°C), respectively. A MDD of smaller than or equal to 2°C was regarded as an indicator of reference conditions. Therefore, when MDD > 2°C, the following equations were used to adjust maximum, minimum temperature, and dew point data:

$$T_{\max_o} = T_{\max} - 0.5(\mathrm{MDD} - 2)$$

$$T_{\min_o} = T_{\min} - 0.5(\mathrm{MDD} - 2)$$

$$T_{d_o} = T_d + 0.5(\mathrm{MDD} - 2)$$

where the subscript "o" was used to indicate data values adjusted to represent the reference (i.e., well-watered) conditions.

References

Alam, M., and Elliott, J. (2003). "Validating the use of an atmometer as an irrigation management tool." *Paper No: 032142*, American Society of Agricultural Engineers, Las Vegas.

Alam, M., and Trooien, T. P. (2001). "Estimating reference evapotranspiration with an atmometer." *Appl. Eng. Agric.*, 17, 153–158.

Allen, R. G. (1996). "Assessing integrity of weather data for use in reference evapotranspiration estimation." *J. Irrig. Drain. Eng.*, 122, 97–106.

Allen, R. G., et al. (2005) *The ASCE standardized reference evapotranspiration equation*, ASCE, Reston, Va.

Allen, R. G., Pereira, S. L., Raes, D., and Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements, Irrigation and Drainage Paper 56*, Food and Agricultural Organization of the United Nations, Rome.

Altenhofen, J. (1985). "A modified atmometer for on-farm ET determination." *Advances in Evapotranspiration: Proc., National Conf. on Advances in Evapotranspiration*, American Society of Agricultural Engineers, St. Joseph, Mich., 177–184.

Altenhofen, J. (1992). "ETgage: A field device for simulating ET." *Proc., Irrigation Association Conf.*, Irrigation Association, Fairfax, Va.

Blanco, F. F., and Folegatti, M. V. (2004). "Evaluation of evaporation-measuring equipments for estimating evapotranspiration within a greenhouse." *Revista Brasileira de Engenharia Agricola e Ambiental*, 8, 184–188.

Broner, I., and Law, R. A. P. (1991). "Evaluation of a modified atmometer for estimating reference ET." *Irrig. Sci.*, 12, 21–26.

Cuenca, R. H. (1989). *Irrigation system design: An engineering approach*, Prentice-Hall, Englewood Cliffs, N.J.

Doorenbos, J., and Pruitt, W. O. (1977). *Guidelines for predicting crop water requirements*, 2nd Ed., *Irrigation and Drainage Paper 24*, Food and Agricultural Organization of the United Nations, Rome.

Frevert, D. K., Hill, R. W., and Braaten, B. C. (1983). "Estimation of FAO evapotranspiration coefficients." *J. Irrig. Drain. Eng.*, 109, 265–270.

Irmak, S., Dukes, M. D., and Jacobs, J. M. (2005). "Using modified Bellani plat evapotranspiration gauges to estimate short canopy evapotranspiration." *J. Irrig. Drain. Eng.*, 131, 164–175.

Jensen, M. E., Burman, R. D., and Allen, R. G. (1990). *Evapotranspiration and irrigation water requirements*, ASCE Manuals and Reports on Engineering Practice No. 70, ASCE, New York.

Legates, D. R., and McCabe, G. J. (1999). "Evaluating the "goodness-of-fit" measures in hydrologic and hydroclimatic method validation." *Water Resour. Res.*, 35, 233–241.

Magliulo, V., d'Andria, R., and Rana, G. (2003). "Use of the modified atmometer to estimate reference evapotranspiration in Mediterranean environments." *Agric. Water Manage.*, 63, 1–14.

Pereira, A. R., Villa Nova, N. A., Pereira, A. S., and Barbieri, V. (1995). "A model for the class A pan coefficient." *Agric. Forest Meteorol.*, 76, 75–82.

Raghuwanshi, N. S., and Wallender, W. W. (1998). "Converting from pan evaporation to evapotranspiration." *J. Irrig. Drain. Eng.*, 124, 275–277.

Snyder, R. L. (1992). "Equation for evaporation pan to evapotranspiration conversions." *J. Irrig. Drain. Eng.*, 118, 977–980.

Temesgen, B., Allen, R. G., and Jensen, D. T. (1999). "Adjusting temperature parameters to reflect well-watered conditions." *J. Irrig. Drain. Eng.*, 125, 26–33.

Willmott, C. J. (1982). "Some comments on the evaluation of method performance." *Bull. Am. Meteorol. Soc.*, 63, 1309–1313.